

# Supernovae, Gamma-ray Bursts, and Nucleosynthesis

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Our team of investigators, headed by principle investigator (PI) Stan Woosley at the Univ. of California, Santa Cruz, has begun the second phase of a DOE Scientific Discovery through Advanced Computing (SciDAC) project to understand stars and the explosive phenomena they produce, especially supernovae of all types, gamma-ray bursts (GRB), and x-ray bursts. We use supercomputer simulations to study the most violent explosions in the universe: supernovae, the powerful explosions of dying massive stars, and gamma-ray bursts, short and bright blasts of intense hard radiation first discovered by LANL scientists. By studying the evolution of massive stars and their explosion as supernovae and gamma-ray bursts, we gain new insights into how the “heavy” elements needed for life, such as oxygen and iron, are forged inside stars through the process of nucleosynthesis. When stars explode, the heavy elements created within them are ejected into space, eventually forming new stars and planets.

Models of these phenomena share a common need for nuclear reactions and radiation transport coupled to multidimensional fluid flow. Our principal goals are not only a better first-principles understanding of supernovae, GRBs, and nucleosynthesis, but also theoretical databases that will allow the more precise and reliable use of supernovae for cosmological distance determination. Our studies of nucleosynthesis in stars and supernovae will be the most complete in the world and will highlight nuclear uncertainties (especially in the  $r$ -process and  $rp$ -process) that will someday be elucidated by the next generation of nuclear physics experiments. In the next 5 years our program will be the only way to address significant gaps in our understanding of these objects and potential systematics in their use as cosmological probes. Our research will be able to directly influence the construction of these experiments, thereby ensuring that they are optimally designed to confront the greatest mystery in high-energy physics and astronomy today: the nature of dark energy.

The central issue in the formation of primordial stars (Population III stars) is their mass. The mass determines the nucleosynthetic yield, the nature of the supernova explosion, whether a black hole remnant is left, and whether the supernova leads to a GRB. We have shown that, in the absence of mass loss, primordial stars between 140 and 260 solar masses explode as pair-instability supernovae. Those higher in mass collapse to form black holes. Simulations show that Population



*Fig. 1. The illustration shows what the brightest supernova ever recorded, known as SN 2006gy, may have looked like. The fireworks-like material (white) shows a pulsational pair instability outburst from a very massive star. In a first supernova the star expelled tens of solar masses of gas that cooled down (red). As the material from the subsequent supernova explosion crashes into the lobes, it heats the gas in a shock front (green, blue, and yellow) and pushes it backward. (Credit: NASA/CXC/M.Weiss).*

III stars form from large condensations of gas and dark matter in which the Jeans mass, i.e., the critical mass for collapse of the gas cloud to a star, is on the order of 500 solar masses. The conclusion from both numerical and analytic studies is that the collapse of this gas does not result in fragmentation. As a result, the final mass of the star is set by feedback processes, the most important of which are photoionization and the associated radiation pressure. It is essential to simulate the formation of the first stars, including these feedback processes, to better constrain their initial masses.

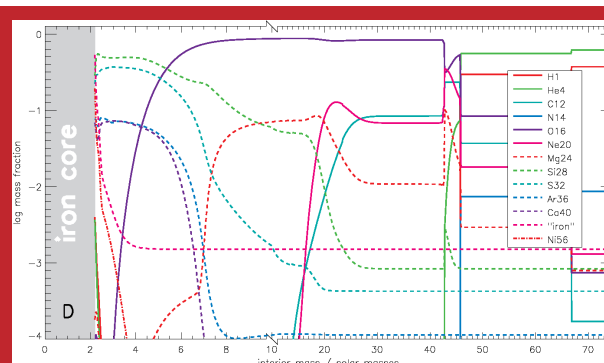
Stars with helium core masses heavier than about 45 solar masses experience a dynamic instability after carbon burning. The conversion of energy into rest mass of electron-positron pairs at temperatures in excess of about  $10^9$  K robs the star of energy that would have gone to increasing the pressure, and as a result the core of the star implodes. This implosion continues until either explosive nuclear burning delivers enough energy to turn it around into an explosion, or a black

hole is formed. For nonrotating stars with helium core masses less than about 130 solar masses, an explosion is the outcome. Kinetic energies of up to  $10^{53}$  erg are possible, with some explosions producing as much as 50 M of iron (as radioactive  $^{56}\text{Ni}$ ). Successful 1D explosion models have been calculated for 40 years, and a recent survey [1] has elucidated the nucleosynthesis expected for the entire range of pair-instability supernova masses. The frontier now is 2D and 3D models with rotation. The pair instability might be partially suppressed or shifted to higher masses by large stellar rotation, but on the other hand rotationally induced mixing can greatly increase the helium core mass for a given initial mass, thus changing the mass range where different outcomes occur to lower mass.

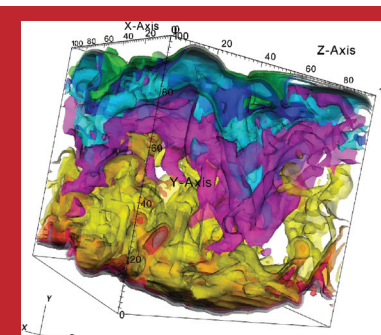
Recently, we reported in *Nature* [2] a model of the extremely luminous supernova SN 2006gy, which exploded last year in a flash 100 times brighter than typically observed in supernovae. We developed a model that allows us to explain that the brilliant flash of light emanating from the star did not come during a single collapse that resulted in the death of the star — the standard model for typical supernova behavior. Instead, very massive stars with initial masses from 100 to 140 solar masses can produce repeated supernova-like outbursts. Very brilliant bursts of light occur when subsequent shells of material collide with one another at some distance from the star. The kinetic energy of the lost material is converted into light at close to 100 percent efficiency as compared with normal supernovae, where this efficiency is only 1 percent or less.

While previous research has already suggested instability of electron-positron pairs leading to supernova behavior, the *Nature* article [2] is the first time research has suggested that such repeated instability in pulses creates very bright supernovae. With this new model, multiple pulses of varying strengths are possible, giving rise to a wide variety of behaviors in massive stars until they unleash their final knockout punch. Understanding pair-instability supernovae and their observability is also a topic of the newly funded LDRD-ER project, “The First Cosmic Explosions” (PI: Alexander Heger).

Type I X-ray bursts (XRBs) are the thermonuclear explosion of a thin layer of hydrogen and helium on the surface of a neutron star. The immense gravitational acceleration compresses this fuel to the point of ignition, and the fuel is rapidly burned. The typical recurrence time between outbursts is a few hours, so multiple bursts can be observed from a single source. Very detailed timing information along



**Fig. 2. Composition of the ejecta of the 110 solar mass star as it finally dies. The iron core mass is 2.18 solar masses and, its outer edge is collapsing at 1000 kms<sup>-1</sup>. A hot proto-neutron star will now form, which, depending on the maximum physically allowed neutron star mass and accretion over the next few seconds, may become a black hole. A separate calculation of a rotating 95 solar mass star with similar final helium core mass gave an angular momentum for the iron core of  $4.3 \times 10^{48}$  erg•s, implying a neutron star rotation rate of 2 ms. This is enough angular momentum that rotation is likely to play a role in the final death of the star, perhaps producing a millisecond “magnetar” or a “collapsar.”**



**Fig. 3. Surfaces of constant entropy in a 3D simulation of two-component combustion in an X-ray burst. Colors indicate different levels of entropy. Fast combustion occurs when hot carbon gets in contact with a layer of cooler hydrogen above it. Preliminary 1D simulations indicate that the entire hydrogen layer will be engulfed within less than 1 ms. This image shows a simulation of 1 m<sup>3</sup> at the interface between hydrogen and carbon when they first get in contact. The thickness of the entire layer is about 10 m (credit Sanjib Gupta T-16).**

with light curves are provided by the Rossi X-ray Timing Explorer satellite. This frequency of bursts and the availability of good instruments has led to a host of discoveries, including the existence of oscillations during the burst. The likely cause of these oscillations is bright spots on the surface on the rapidly rotating (300-600 Hz) neutron star. These oscillations suggest that the burning is spreading across the neutron star. At LANL XRBs are also studied as part of a large new directed research project on cosmic explosions (PI: Sanjay Reddy, Co-I: Alexander Heger).

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[1] A. Heger and S. E. Woosley, *Astro phys. Jour.*, **567**, 10:532-543 (2002).

[2] S. E. Woosley, S. Blinnikov and A. Heger, *Nature*, **450** (7168), 390-392 (2007).

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